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Kansainvälinen luokka International class	A61B
Keksinnön nimitys Title of invention	

"Procedure for the analysis of physiological signal"
(Menetelmä fysiologisen signaalin analysoimiseksi)

Hakemus on hakemusdiaariin 30.09.2002 tehdyn merkinnän mukaan siirtynyt **Firstbeat Technologies Oy:lle, Jyväskylä.**

The application has according to an entry made in the register of patent applications on 30.09.2002 been assigned to **Firstbeat Technologies Oy, Jyväskylä.**

Täten todistetaan, että oheiset asiakirjat ovat tarkkoja jäljennöksiä Patentti- ja rekisterihallitukselle alkuaan annetuista selityksestä, patenttivaatimuksista, tiivistelmästä ja piirustuksista.

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E T U O I K E U S T O D I S T U S
P R I O R I T Y   D O C U M E N T

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A PROCEDURE FOR THE ANALYSIS OF PHYSIOLOGICAL SIGNAL

Inventors: Sami Saalasti, Joni Kettunen, Aki Pulkkinen
Assignee: Atmosport Oy, Finland

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6,104,947	Heikkilä
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BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to the monitoring of body functions, in particular to methods that are aimed to describe exercise and physical activity. More specifically, the invention relates to a system for deriving predictions on body fatigue and recovery during physical exercise and while recovering from such exercise.

The current invention presents a procedure for predicting body fatigue during exercise and recovery from exercise on the basis of physiological measurement.

2. Description of the Prior Art

The control of exercise intensity, duration, and recovery from the exercise are key elements in maintaining and achieving a good physical fitness. The control of exercise boundaries is especially important in health enhancing physical activity, wherein exercise is directed to improve health and fitness. In particular, for individuals that suffer from some clinical condition, such as cardiovascular disease, it is extremely important to maintain physical activity within safe limits.

The accumulation and reduction of the effects of exercise on the body is described in this document by two related concepts, body fatigue and recovery. Body fatigue is defined as a decrease of physiological resources due to the effects of exercise and physical activity. Recovery from physical exercise is defined as the restoration of physiological resources due to accumulation of body fatigue during exercise.

It has been generally accepted that especially the balance between exercise and recovery is important in athletic training and sports. Optimal training requires enough rest to recover from the exercise. This may be a hard goal to achieve for a person engaged in physical exercise and training, since exercise methods are mainly based on experience and general knowledge on the physiology. If exercise bouts are too mild, no positive training effect occurs because disturbance to the homeostasis has been minimal. On the other hand, if exercise bouts are scheduled too severe and too frequent, negative training effect may occur because bodily functions have not been restored properly. To gain positive training effect exercise bouts must be timed optimally, in order to give the body a chance to adapt this new level of functioning.

To summarize, a method that would give feedback on body fatigue and time required for recovery on the basis of individuals own physiological characteristics would be certainly helpful to many individuals engaged in physical exercise and fitness training and would potentiate more optimal and safe training schedules.

Oxygen consumption (VO_2), that is, the rate of oxygen intake, is a central mechanism in exercise and provides a measure to describe the intensity of the exercise. Oxygen is needed in the body to oxidize the nutrition substrates to energy and therefore VO_2 is very tightly coupled with the energy consumption requirements triggered by exercise and physical activity. American College of Sports Medicine Position Stand of physical activity. recommendations for exercise prescription (ACSM 1998) suggests the use of VO_2 on the measurement of physical activity.

The level of oxygen consumption can be measured by different methods. The most accurate methods rely on the measurement of heat production or analysis of respiratory gases but require heavy measuring equipment and are therefore restricted to the laboratory environment. There are also more cost effective and practical means to estimate oxygen consumption using indirect methods based on the measurement of, for example, heart rate, ventilation, skin temperature, or movement. In particular, there is a close relationship between heart rate and oxygen consumption during exercise as increased oxygen consumption in the muscles requires an increase in circulatory volume. Heart rate is a major determinant of the circulatory volume and often provides a reasonable estimate of the oxygen consumption.

Maximal oxygen consumption (VO_{2max}) is defined as the maximal oxygen intake during exhaustive exercise and denotes person s ultimate capacity of aerobic energy production. Usually this is achieved by stepwise exercise protocol to a voluntary exhaustion (maximal stress test), during which the oxygen uptake is measured. Also non exercise methods are available to estimate person s aerobic capacity based on individual characteristics such as, for example, age, sex, anthropometric information, history of physical activity, or resting level physiological measurement (e.g. Jackson et al. 1990).

Knowing the absolute oxygen consumption rate in which a person is exercising and the maximal attainable oxygen consumption of the same person, exercise intensity can be described as a percentage of the maximum. This may be efficient, as maximal values of VO_2 can vary markedly between subjects. Thus, two persons that differ in their maximal VO_2 but exercise at the same relative intensity have similar exercise impact on their bodies.

Athletic training and physical exercise in general has acute effects on body resources and body fatigue. The accumulation of body fatigue is determined by the characteristics of the exercise, including intensity, duration, and phase of the exercise. At high exercise intensities the level of energy requirements increase and induce a proportional raise in the reduction of available body resources. The mobilization of body resources is associated with accelerated physiological function and involves increased levels of oxygen consumption, circulation, ventilation, and hormone secretion (e.g., catecholamines). Metabolic function during exercise is characterized by increased rate of energy release from carbon hydrates and body fats, and involve also by products such as lactate, all of which reduce the level of metabolic resources available in the body.

The physiological processes of recovery from exercise involve a renewal of consumed body resources and are generally characterized as opposite to those during exercise. The level of physiological function shows attenuation towards normal levels. The recovery of metabolic resources involves replenishment of energy stores (e.g., glycogen) and removal of exercise induced by products (e.g., lactate). The process of recovery requires oxygen and therefore VO_2 remains elevated after exercise and may be used as an composite indicator of the replenishment of the resources in the body. This indicates that the extend of exercise induced fatigue may be determined by the characteristics of the recovery process after the exercise.

The prior art has also documented some work on the measurement of exercise levels and stress on the basis of heart rate variability (HRV). HRV denotes the extent of rhythmic changes evident in the heart rate. The relationship of the heart rate variability to the exercise and stress is well known and documented in the prior art. Golosarsky and Wood (U.S. patent 5,891,044), Heikkilä and Pietilä (U.S. patent 6,104,947), and Hoover (U.S. patent 6,212,427) have all implemented a technique of determining the stress caused by exercise using different types of indices based on HRV. These methods usually require preset individual thresholds and state declarations, as defined by the user or history values, to give an estimate of the level of stress caused by the exercise and workload. The described methods are relatively simple, easy to implement and provide feedback on the acute exercise load.

It has been shown earlier that the amplitude of the HRV is associated with the intensity of physical activity. It is also known that HRV is associated with the aerobic threshold of the metabolism, which usually occurs at approximately 50 75% of maximal intensity in exercise (Tulppo et al., 1996). It is therefore clear to anyone experienced in the art that the HRV is primarily a measure of the intensity of the exercise and therefore provides little if any information on the dynamic phenomena of accumulation of body fatigue and process of recovery during different phases of the exercise. Thus, the described measures are primarily dependent on the instantaneous characteristics of the exercise and are not capable of adapting to temporal dynamics in different phases of the exercise. For example, during a short but intensive exercise HRV reflects high stress than considerably longer exercise with lower intensity, although in this case the longer duration exercise would accumulate, in effect, higher levels of body fatigue and a longer time required for recovery.

Prior art has documented work on deriving information on the accumulation of body fatigue and exhaustion as due to physical workload. Bernard, Sherwin, Kenney, William and Lewis (U.S. patent 4,883,063) have presented a method for monitoring heat stress, as especially occurring in a hot factory environment. The levels of heart rate and skin temperature are used within predefined temporal window to monitor potential exhaustion and a warning is triggered if a predefined threshold value is passed. The solution also includes an assessment of recovery on the basis of heart rate measurement, during which the person has to stay at rest for few minutes.

It is apparent to one skilled in the art that the method of Bernard et al. is designed for the analysis of tonic workload with known properties (e.g., heat stress). In most real life occasions, intensity of the exercise may vary markedly with different phases of the exercise due to, for example, conditions (e.g., up and down hills), training mode (walking and running), or any means of controlling exercise intensity due to, for example, sports characteristics, physiological state or training protocol. The method of Bernard et al. is dependent on the instantaneous levels of the heart rate and skin temperature and therefore, in a similar manner to the methods based on HRV, does not include history information on the accumulation of body fatigue. The method may provide reliable results within constant working environment with known workload, but it is clearly not sufficient for monitoring body fatigue during exercise, wherein the level of heart rate is heavily dependent on the intensity of the exercise and thus does not indicate level of exhaustion.

The method presented by Bernard et al. has also some limitations with regards to the monitoring of recovery. The estimation of the recovery is somewhat problematic in the described method, since it requires few minutes of rest and is not therefore applicable to continuous monitoring of recovery within dynamic changes in exercise phases and intensities. In general, the method does not involve a differential estimation of the recovery component, which impairs the estimation of the recovery during dynamic exercise, wherein a decrease in exercise intensity may induce a reduction in recovery state. All this implies that the described method is not capable of producing continuous information on recovery and does not predict the amount of recovery required in advance to the onset of actual recovery.

To summarize, the monitoring of exercise effects on the body is not possible with a model that does not take into account the fact that exercise has a cumulative impact in the

accumulation of the body fatigue and that it is not equal at different intensities and phases of the exercise. The description of the prior art clearly indicates that the described methods are highly dependent on the exercise state and do not contain cumulative information on the accumulation of fatigue through the exercise. The described methods neither do potentiate a continuous monitoring of recovery, which would be most important in any condition wherein the exercise is dynamic and the user would benefit from the information on the onset and progress of recovery.

OBJECTS AND SUMMARY OF THE INVENTION

The object of the present invention is to provide new types of methods and apparatuses for monitoring and controlling the processes body fatigue and recovery of persons engaged in fitness training and physical exercise. According to the preferred embodiments, the innovation potentiates the monitoring of the body fatigue during exercise and recovery from such without the need for any external professional aid. The invented procedure is based on the measurement of a physiological parameter that describes the intensity of the exercise, such as heart beat, movement, ventilation, skin temperature, or oxygen consumption.

The innovation offers a method of tracking continuously the influence of exercise on body fatigue and recovery from exercise without the need of a restricting to laboratory environment or equipments. The procedure can be used to provide real time feedback on exercise status to optimize physical exercise, sports training and recovery, and to provide predictions of time requirements for body recovery and exhaustion.

The present innovation includes several features that clearly differentiate it from the prior art and provide new benefits for the end user. (1) The formation of the body fatigue index (BFI) is based on a set up wherein the actual extent recovery time required following the exercise are used to determine the properties and dynamics of the accumulation of the body fatigue effect. (2) Given that the physiological determinants of the body fatigue may be measured only after exercise while recovering, the present procedure predicts the expected recovery requirements already during the exercise, in advance to the actual recovery after the exercise. (3) After exercise, the comparison of the actual monitoring of recovery with the predictions based on BFI provides information on the progress of the recovery process. (4) The procedure is capable of including information on the past and is not a simple state measure of exercise stress, which potentiates the use of the procedure in tracking exercise effects during exercise with dynamic shifts in intensity and duration.

The computational part of the exercise phase dependent accumulation of BFI, as solved in the present innovation, may be generally described with the following functional notation,

$$BFI_{t+1} = BFI_t + f(BFI_t, Exercise\_intensity_t)$$

wherein the recursive implementation of the accumulation of the BFI has the benefit of not having requirements for knowing a priori the beginning time of the exercise and different durations of exercise at varying intensities. As with other solutions, wherein the increment in the body stress is dependent on the instantaneous characteristics of the exercise, as derived from, for example, estimated oxygen consumption, the present

solution contains inherently history information on the exercise and is capable of adapting to dynamic changes in exercise intensity with different phases of the exercise.

A reader with experience in the art may easily perceive that the level of sophistication and function in the present innovation is advanced to the prior art and that the present innovation involves several features that are clearly distinguishable. In particular, the present innovation is not being based on direct monitoring of measures related to exercise state, such as heart rate variability.

The invention may be applied to and in association with devices such as heart rate monitors and other mobile or wearable computing devices, fitness equipments, and software, wherein there is the capability to receive information on one or more physiological measures, such as oxygen consumption, heart beat, skin temperature, or respiratory activity. This procedure may also be highly useful in the context of the ambulatory ECG and heart beat analysis systems wherein it is of importance to detect whether the source of increased heart rate is based on exercise and physical activity induced effects on the body or due to other source that has an accelerative effect on the cardiovascular system.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1. The relationship between time in minutes and oxygen depth left in percents presented with an empirical data. The figure also includes a mathematical model estimated from the data.

Figure 2. The upslope component of the BFI as a function of previous level of accumulated BFI and exercise intensity.

Figure 3. The weight function to combine down and upslope components as a function of exercise intensity.

Figure 4. A flowchart presenting the calculation of the BFI and explanation of flowchart symbols.

Figure 5. The calculation of downslope component and recovery history.

Figure 6. The calculation of upslope component.

Figure 7. A flowchart presenting the modeling of exhaustion and recovery times.

Figure 8. Oxygen consumption and BFI during exercise.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The innovation is described here with the aid of an example implementation. It should be noted that the described system is not bound to any specific model or specifications, but rather, different alterations, forms, and improvements are possible and are in line with the

spirit of the innovation. Thus, the following merely contains a description of the preferred embodiments of the innovation.

The preferred embodiment applies oxygen consumption as the input physiological measure. Given the relative difficulty in measuring oxygen consumption directly, the level of VO_2 is estimated on the basis of heart beat, for example, by applying a polynomial equation or a more complex function relating heart beat level to the level of VO_2. However, it is important to notice that whereas the VO_2 is used here to index exercise intensity, also other measures, such as heart beat level, respiratory activity, skin temperature, and movement, may be used directly without any transformation to VO_2 to estimate exercise intensity and physical activity, or may be used indirectly by using a transfer function to estimate VO_2.

The input value of the VO_2 is presented as proportional to the maximum in the illustrated example of the preferred embodiment of the innovation; it should be, however, clear to anyone experienced in the art that the scope of the present innovation does not in any manner limit the use of any of the input measures or derived measures in either absolute values, or as proportional to maximum, minimum, or both maximum and minimum (so called reserve) values.

In this innovation, the scale and measurement of body fatigue index (BFI) is performed through the estimation of the level of recovery demands after exercise. The preferred embodiment described here uses the magnitude of the VO_2 that is in excess to the acute body demands determined by the level of physical activity as an index of body fatigue. This is based on the notation that the extent of recovery processes to be carried out in order to return to the normal homeostasis of the body and therefore the extent of BFI are reflected in the quantity of excessive VO_2 consumption after the exercise. Another preferred or alternative methods of estimating the extent of recovery demands would consist of determining the extent of additional heart rate or heart rate variability level when compared to baseline, or the recovery of lactate levels after the end of exercise.

It is important to understand that the purpose of using physiological measures of recovery is to provide preset values on the dynamics of how body fatigue accumulates. In another words, these measures provide a scaling for the accumulation of BFI upon different duration, intensity, and phases of physical training. Thus, for example, the amount of increased oxygen consumption after the exercise may be used to indicate the degree of body fatigue that is accumulated during the exercise. Nevertheless, as indicated above, the present innovation is not restricted to the above measures only, but rather, allows the use of other types of measures to index the amount of recovery demands after exercise.

Given that the measures of body fatigue and recovery can be monitored only after the exercise, when the actual recovery is progress, poses a problem for the generation of feedback already during the exercise for a user engaged in exercise and physical training. The present innovation solves this problem by predicting the extent of recovery requirements already during the exercise, before the recovery has actually occurred, which allows to represent feedback on exercise status and body fatigue on a real time basis. This procedure is based on an iterative model that predicts the post exercise increase in the oxygen consumption during the exercise. The iterative, real time solution of predicting post exercise increase in oxygen consumption may have been possible by fitting a

recursive, real time capable algorithm to the database consisting of recovery assessment in combination with different exercise intensities and durations.

The BFI is formed in a recursive manner using the previous values of the BFI and the intensity of the exercise at the moment. The modeling of BFI and recovery is based on the computation two components, an upslope component and downslope component. Figure 4 illustrates an overall view of the system.

Equation 1

$$y(T) = \begin{cases} c_1 \cdot T + c_2, & T >= \dfrac{c_2}{(c_3 - c_1)} \\ c_3 \cdot T, & else \end{cases}$$

$$c_1 = b_1 \cdot P^4$$
$$c_2 = b_2 \cdot P$$
$$c_3 = c_1 + b_3 \cdot P,$$

$$b_1 = 1.2287 \cdot 10^{-7}$$
$$b_2 = 0.5206$$
$$b_3 = 0.0087.$$

$$y^{-1}(old\_fatigue) = \begin{cases} \dfrac{old\_fatigue - c_2}{c_1}, & \dfrac{old\_fatigue - c_2}{c_1} >= \dfrac{c_2}{(c_3 - c_1)} \\ \dfrac{old\_fatigue}{c_3}, & else \end{cases}$$

$$upslope(\Delta t, old\_fatigue) = \begin{cases} y(\Delta t + y^{-1}(old\_fatigue)), & old\_fatigue > 0 \\ y(\Delta t), & else \end{cases}$$

Equation 1 summarizes the calculation of the upslope component in this example. It is a composition of genuinely ascending piecewise linear function y and its inverse y^{-1}. Function y models the upslope as a function of time T and exercise intensity P. To model the BFI already cumulated in the system the inverse y^{-1} solves the time needed to reach the former BFI level with current intensity. The addition (i.e., sum) of two time components, the time difference Δt and $y^{-1}(old\_vatigue)$ is used to calculate the new upslope value with the function y. Time difference Δt expresses the distance in minutes between the former and current BFI values.

In this manner, the upslope component is capable of responding to the duration of exercise and past accumulation of body fatigue without forcing the model or user to classify the end and beginning of the exercise. The function relating exercise intensity and

accumulated BFI to the upslope (i.e., increasing) component of the BFI is illustrated in Figure 1. The intensity of the exercise is in proportional units (e.g., percents).

Equation 2

$$downslope(\Delta t) = \frac{1}{c^{\Delta t}},$$

$$c = 1.1$$

The downslope component is a genuinely decreasing function of time. The function is based on the modeling of the recovery after physical exercise, wherein the progress of the recovery is determined by a physiological measurement, such as the increased rate of oxygen consumption after the exercise, as used in the example of the preferential embodiment. Other useful indices would be the extent of heart rate that is above rest or acute physical demands, decreased HRV, and lactates, the recovery of all of which components to resting levels is determined on the exercise characteristics and accumulated body fatigue. In the present embodiment the progress of the decrease in BFI is based on a proportional model of decrease as a function of recovery time, that is, the shape of the proportional recovery function is not affected by the quantity of BFI. Figure 2 illustrates the model of the proportional recovery, which is based on the empirical data on the quantification of the rate of excessive oxygen consumption after the exercise. The recovery is exponentially inversely proportional to time, i.e., at the beginning the progress of the recovery is the fastest. An example implementation of the formulas and parameters of the downslope component are presented in Equation 2.

Exercise and physical activity may consist of several periods of increased physical activity and following period of recovery. These "exercise bouts" and periods of increased physical activity may be described as separate components that each have their own recovery function (i.e., downslope) and which, when combined, form the total amount of BFI. In this manner, the characteristics of the physical activity in the near past affect the progress of recovery by including the computation of separate downslope components for previous bouts of exercise and physical activity.

A BFI peak is defined as the value of BFI at time point wherein the current value of BFI is higher or equal to the previous value of BFI and the next value of BFI is lower than the current value of BFI. The value of each BFI peak is stored in the system. The system has two alternative mechanisms of handling the new BFI peaks.

(1) If no BFI present before the onset of physical activity, then first BFI is always taken as the basis of computing downslope component.

(2) If a BFI peak is below to previous peak its downslope is calculated from the difference between the peak and the BFI where the BFI started to increase. The BFI where increasing starts is the one where both BFI before and after are more than the current BFI.

In some point the effect of the prior peaks in BFI are no longer stored in the system or taken to consideration in the accumulation of increases in BFI. These incidents may be defined with a threshold value (e.g., preferably absolute quantity) or based on other criterion, such as the percentual distribution of the recovery.

In current embodiment the BFI peaks are ignored for the simplicity of the calculation. However they become important if more accuracy is required and the phenomenon is wanted to describe more precisely. With the current embodiment the BFI is not affected by the history implying that the current value is only affected by the previous BFI, current intensity and time between the measurements.

Equation 3

$$zmf(x,p_1,p_2)=\begin{cases} 1.0, & x \le p_1 \\ 1.0-2.0\cdot\left(\dfrac{x-p_1}{p_1-p_2}\right)^2, & x>p_1 \wedge x \le \dfrac{p_1-p_2}{2} \\ 2.0\cdot\left(\dfrac{p_2-x}{p_1-p_2}\right)^2, & x>\dfrac{p_1-p_2}{2} \wedge x<p_2 \\ 0.0, & x \ge p_2 \end{cases}$$

Equation 4

$$y_1(\Delta t, old\_fatigue) = downslope(\Delta t)\cdot old\_fatigue$$
$$y_2(\Delta t, old\_fatigue, P) = (1-zmf(P,0,1))\cdot upslope(\Delta t, old\_fatigue) + zmf(P,0,1)\cdot y_1(\Delta t, old\_fatigue)$$
$$body\_fatigue = \max(y_1(\Delta t, old\_fatigue), y_2(\Delta t, old\_fatigue, P))$$

The combination of the down and upslope components is presented in Equation 4. The first function y_1 expresses the level BFI as indicating body fatigue left in the system. The second function y_2 is a function of time difference between the present and old BFI, the exercise intensity and latter BFI value. It gives a combination of the down and upslope components as a weighted average where the weights are expressed as a function of exercise intensity. An example of the weights of the components determined as a function of exercise intensity is illustrated in Figure 3 and Equation 3. The maximum of these functions is used as a new BFI.

The combination of upslope and downslope components provides the difference in the BFI from the previous value of the BFI. Correspondingly, the new level of BFI is obtained from summing the combination of upslope and downslope components with the previous value of the BFI. The BFI may be used as such, wherein it denotes the level of the predicted measure (e.g., the expected amount of additional VO_2 consumption during recovery) or as in proportional units, where the index is being referenced to preset or individual maximum values of body fatigue.

Time to exhaustion refers to the estimated time (e.g., in minutes) that the user can engage within present level of exercise intensity before the occurrence of physical exhaustion. Time to exhaustion is defined with a threshold value indicating the maximum possible body fatigue for the individual and with an inverse of the upslope component indicating the time to reach the threshold with the current exercise intensity.

Recovery time refers to the estimated time (e.g., in minutes) that will be taken for the user to perform acute recovery from the exercise, given that the user would begin recovery at the time instant. Recovery time is calculated from the inverse function of Equation 1 and recovery threshold, i.e. the time needed to reach the recovery threshold is estimated. The recovery history is used as before. Figure 7 presents a flowchart illustrating the calculation of exhaustion and recovery times.

The prediction of the recovery of the autonomic nervous system, in specific heart rate and heart rate variability, from exercise and physical activity related effects potentiates the monitoring of the progress of the actual recovery process. This may be achieved by applying, as a preferred embodiment, a comparison between observed heart rate level and predicted heart rate level. If the heart rate level is higher than that predicted indicates that recovery is progressing with a slower rate than that expected and, in a similar manner, if the heart rate level is lower than that predicted indicates that recovery is progressing with a faster rate than that expected. This procedure enables the production of information on the rate of recovery on the basis of comparing the observed level of heart rate to predicted level of heart rate. The advantage of this method is that it provides a method of evaluating the rate of recovery to the expected rate of recovery due to cumulated body fatigue, thus providing information on the progress of recovery from exercise as associated with the present state of the body.

It is well known that, following exercise and physical activity, cardiovascular system and in particular heart beat level shows an increased level of activity. This poses a problem for the analysis of ambulatory heart beat signal, wherein it is of importance to differentiate physical activity induced autonomic nervous system reactivity from other sources of reactivity, such as, for example, physical activity, or physical or mental stress. As an application, and in accordance with the present innovation, BFI, shape of recovery and the predicted recovery levels of heart rate level and heart rate variability levels may be used to differentiate the effects of physical activity associated autonomic nervous system reactivity from other sources of reactivity. When using this application, a recovery function of heart rate and HRV based on empirical data similar to that as presented in Figure 2 provides a model based prediction for the recovery of heart rate level after exercise and potentiates a detection and differentiation of exercise induced reactivity from other sources of reactivity.

The level of predicted oxygen consumption during the recovery may be also used to correct the estimates of oxygen consumption that are based on the use of heart rate level, since the level of heart rate may be provide accurate information on the oxygen consumption level during recovery from exercise and physical activity.

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Claims

What is claimed is:

1. a method for deriving information on exercise and physical activity induced changes in body fatigue, characterized by
   a. the use of information on the intensity of exercise or physical activity as an input to the procedure, as obtained from (i.e., the described procedure may be implemented in the connection of the following input variables)
      i. parameters from the measurement of a physiological signal, such as
         1. oxygen consumption
         2. heart beat
         3. respiratory interval
         4. ventilation
         5. movement
         6. skin temperature
      ii. information on the intensity of exercise or physical activity as obtained using a mathematical function to the parameters from the measurement of a physiological signal, such as
         1. heart beat
         2. respiratory interval
         3. ventilation
         4. movement
         5. skin temperature
      iii. information on the level of oxygen consumption as obtained using a mathematical function to the parameters from the measurement of a physiological signal, such as
         1. oxygen consumption
         2. heart beat
         3. respiratory interval
         4. ventilation
         5. movement
         6. skin temperature
      iv. the use of at least one feature in (i iii) and using proportional units wherein the measured values to the given individuals minimum, maximum, or both minimum and maximum values at the given measurement parameter, wherein the minimum or maximum values in the particular parameter may be either (1) inputted by the user, (2) detected by the system, or (3) determined by the system
   b. the generation and use of a model relating a measured quantity of body requirements for recovery after exercise and physical activity to the determination of the accumulation of body fatigue during exercise and physical activity (the upslope component of the body fatigue index, BFI), based on the following steps
      i. applying data based on physiological recordings of the quantity of body requirements for recovery after exercise and physical activity to quantify and calibrate the accumulation of the body fatigue

1. definition of the quantity of body requirements for recovery after exercise or physical activity based on the comparison of the measured level of physiological parameters to the intrinsic (i.e., spontaneously occurring) level of the same parameter for the given individual, characterized by the use of at least one of the following physiological parameters
    a. heart beat
    b. heart beat variability
    c. oxygen consumption
    d. lactate
2. definition of the quantity of body requirements for recovery after exercise or physical activity based on the comparison of the measured level of physiological parameters to the resting baseline (i.e., without stimulation at rest) level of the same parameter for the given individual, characterized by the use of at least one of the following physiological parameters
    a. heart beat
    b. heart beat variability
    c. oxygen consumption
    d. lactate
3. definition of the quantity of body requirements for recovery after exercise or physical activity based on the comparison of the measured level of physiological parameters with the level of physiological parameters as predicted by the present intensity of exercise and physiological activity, characterized by the use of at least one of the following physiological parameters
    a. heart beat
    b. heart beat variability
    c. oxygen consumption
    d. lactate
4. definition of the quantity of body requirements for recovery after exercise or physical activity based on the determination of the dynamic characteristics of the rate of recovery, characterized by the use of at least one of the following physiological parameters in combination with a mathematical function,
    a. heart beat
    b. heart beat variability
    c. oxygen consumption
    d. lactate

ii. the generation of a static model associating information on the quantity of body requirements for recovery after exercise or physical activity (section i above) to the information on the characteristics of the exercise and physical activity, characterized by

1. the use of temporal information on the duration and phase of the exercise or physical activity

a. duration of the exercise and physical activity in time units
b. phase of the exercise and physical activity

2. intensity of the exercise or physical activity
   a. based on physiological measurement of oxygen consumption
   b. based on physiological measurement of heart beat level
   c. based on the work load as determined by the characteristics of the exercise or physical activity (e.g., distance, equipment load or resistance)
   d. based on any of the methods described in (a c above) and using instead of absolute values proportional values adjusted to maximum and/or minimum of the values for the given parameters for the user
3. the use of a mathematical model combining features characterizing exercise and physical activity (sections 1 2 above) by, for example, presenting the distribution of the temporal length of the exercise as conditional to the intensity of the exercise or vice versa

iii. the determination of the properties of the dynamic accumulation of the body fatigue by applying a quantitative model that determines the quantity of body requirements for recovery after exercise or physical activity (i.e., body fatigue index, BFI) on the basis of the information on the intensity of exercise or physical activity (section i), being characterized by the following properties

1. implementing a recursive model that determines BFI, having at least two of the following characteristics
   a. using information on the intensity of exercise or physical activity as an input to the model (as defined in section 1 a i iv, at the beginning)
   b. using information on the previous prediction value of BFI as an input to the model
   c. applying information on the combined plane of information on the intensity of exercise or physical activity (section a above) with the information on the previous value of the BFI (section b above), as combined with a mathematical function
   d. use of information on the phase of the exercise, such as especially during the beginning and end of the exercise and after changes in the intensity of the exercise
2. provides predictions on the quantity of body requirements for recovery after exercise or physical activity already during the exercise or physical activity, characterized by predictive information on
   a. above resting level heart beat
   b. below resting level heart beat variability
   c. above resting level oxygen consumption

d. above resting level lactate

3. has the property of providing information on a real time basis
4. optimization of the recursive mathematical function relating the intensity of exercise and physical activity and cumulated body fatigue as determined by the quantity of body requirements for recovery after exercise or physical activity to the actual measures of the quantity of body requirements for recovery after exercise or physical activity (as defined in section 1 b i, 1 4) using a statistical criterion that minimizes the deviation between the predicted values and observed values (e.g., minimizing the mean squared difference or the mean absolute difference between the observed and predicted values, or maximizing the proportion of observed variance explained by the predictions produced by the model, or by applying other type of function)
5. denoting the accumulation (upslope) component of the BFI as a function of the present increase in the quantity of body requirements for recovery after exercise or physical activity, being characterized by the following properties
    a. the measure provides values of the upslope accumulation component of the BFI at any given time during the exercise or physical activity or other time of use
    b. the measure is based on an model wherein the accumulation body fatigue as defined by the quantity of body requirements for recovery after exercise or physical activity is based on the increase in the quantity of body requirements for recovery after exercise or physical activity that would exist from the previous time unit if the user would stop the exercise or physical activity and begin recovery

c. the generation and use of a model estimating recovery and decrease in BFI (the downslope component of the BFI), based on at least one of the following steps
    i. based on the database containing physiological measurement during recovery from exercise or physical activity, characterized by at least on the following features
        1. heart beat measurement
        2. heart beat variability measurement
        3. oxygen consumption measurement
        4. lactate measurement
    ii. the fitting of a mathematical function of the time dependent recovery of a physiological measure described in section (i) and characterized by at least one of the following features (preset curve of recovery rate as based on the experimental database of physiological measurements)
        1. the fit of the model is obtained with a one dimensional transformation of time with a linear, nonlinear, exponential,

or any other means of a function that has the property of decreasing gradually as a function of increase in time

2. the fit of the model is obtained with a multidimensional transformation of time and body fatigue characteristics by using any multidimensional function that has the property of decreasing gradually as a function of increase in time
3. fit of the model is obtained from an empirical measurement based on the history information on users recovery

iii. the scaling of the mathematical function described in (ii) into proportional units
iv. detection of BFI peaks as a difference between three BFI values. A BFI peak occurs if the BFI is higher than both the following and previous BFI values.
v. the computation of the rate of recovery by (1) determining the temporal phase of the recovery using the time window from the previous peak in BFI, (2) and determination of the rate of recovery by multiplying the proportion of recovery left at the temporal phase of the recovery with the absolute value of the BFI
vi. subtracting the extent of recovery in BFI, as determined in (i v), from the previous values of BFI

d. the combination of the upslope and downslope components
   i. using a transfer function with weights for the upslope component as a function of the exercise or physical activity intensity based on a physiological measurement and features described in 1a
   ii. using a transfer function with weights for the downslope component as a function of the exercise or physical activity intensity based on physiological measurement and features described in 1a
   iii. the summation of the upslope and downslope components with the previous state of the BFI provides present state of the BFI

2. A system according to Claim 1, including a during exercise prediction of the time interval requirements for acute recovery after the exercise, characterized by
   a. An input from the accumulated BFI
   b. A computation of the recovery function on the basis of the BFI, assuming that there will be no further cumulative increase in the body fatigue due to continuing exercise (i.e., assuming that the person would be at rest and recovering)
   c. Denoting the time required for recovery according to the determination of the time point wherein in a certain level of the recovery has passed, wherein the determination of the level may be characterized by at least one of the following
      i. the determination of the cut off level on the basis of the certain, percentually determined fixed point in the recovery function (see claim 1 c)
      ii. the determination of the cut off level on the basis of the absolute level of BFI left (see claim 1 c)
   d. Using an inverse function of the equation 2 to solve the problem in section (c) by estimating time where the current BFI is less than the predefined recovery threshold.

3. A system according to Claim 1, including the prediction of the time interval after which the user engaged in exercise and physical activity is expected to become exhausted due to accumulation of body fatigue that is induced by continuing exercise and physical activity in the same intensity
   a. A parameter describing the maximum amount of body fatigue that the individual user can maintain, based on one of the following criteria
      i. User input
      ii. Based on the computation based on user input of individual characteristics such as age, weight, activity class and fitness
      iii. Based on the determination of the user properties on the basis of the data
      iv. Based on the previous history information on the exercise related accumulation of the body fatigue
   b. A procedure determining the time required for the body fatigue to increase in to the individuals maximum values (as defined in b above) assuming current intensity of exercise and physical activity
      i. A calculation of the inverse function of the upslope component illustrated in equation 1 to determine the time needed to reach individual maximum

4. A system according to Claim 1, including the use of information on the increased heart beat level during recovery on the classification of increased heart beat level and decreased heart rate variability
   a. The classification of the time instant to either recovery or non recovery on the basis of information on the recovery of BFI and heart beat level or heart rate variability level (see claim 1 c)
      i. determination of the cut of level of recovery process using one of the following criteria
         1. the determination of the cut off level on the basis of the certain, percentually determined fixed point in the recovery function
         2. the determination of the cut off level on the basis of the absolute level of BFI left
      ii. the classification of the time instant either (1) including recovery (recovery component active, BFI above the cut off level) or (2) not including recovery, where the BFI is either below the cut off level or recovery component is not active
   b. the use of information obtain in section (b) to classify the source of increased heart beat level or decreased heart rate variability level to either include recovery or not to include recovery and to apply the classification information in further analysis of heart beat data

5. A system according to Claim 1, wherein information on the level and recovery of oxygen consumption is used to enhance the accuracy of oxygen consumption estimation during recovery from exercise

6. A system according to Claim 1, wherein information on the level of BFI is used to control for the addition (drift) of heart rate during cumulative exercise and the use

of the exercise drift controlled heart rate in the estimation of oxygen consumption level instead of non drift controlled heart rate signal

7. A system according to Claims 1 6, wherein the user is given feedback on information relating to exercise, physical activity, oxygen consumption, body fatigue and recovery, and in general relating to the contents of the Claims 1 6

L3

ABSTRACT

The present work describes a method of deriving a predictive and informative measure of exercise induced fatigue and recovery from exercise. The procedure may be preferentially used in connection with ambulatory, continuous heart beat measurement, but may be applied in combination with other physiological measures as well. The invented procedure is based on real time modeling of the physiological dynamics during exercise and recovery from exercise. In particular, the invention provides information on body fatigue and time required for recovery through a procedure, wherein the demand of body recovery due to exercise induced fatigue is predicted already during the exercise, in advance to the actual recovery occurring after the exercise. This method provides dynamic measures of body fatigue and recovery at different temporal phases and varying intensities of exercise. The invention is particularly useful in noninvasive monitoring and prediction of body fatigue and recovery during exercise, especially whenever information and care is needed to attain optimal and safe training.

L 4 /

Figures

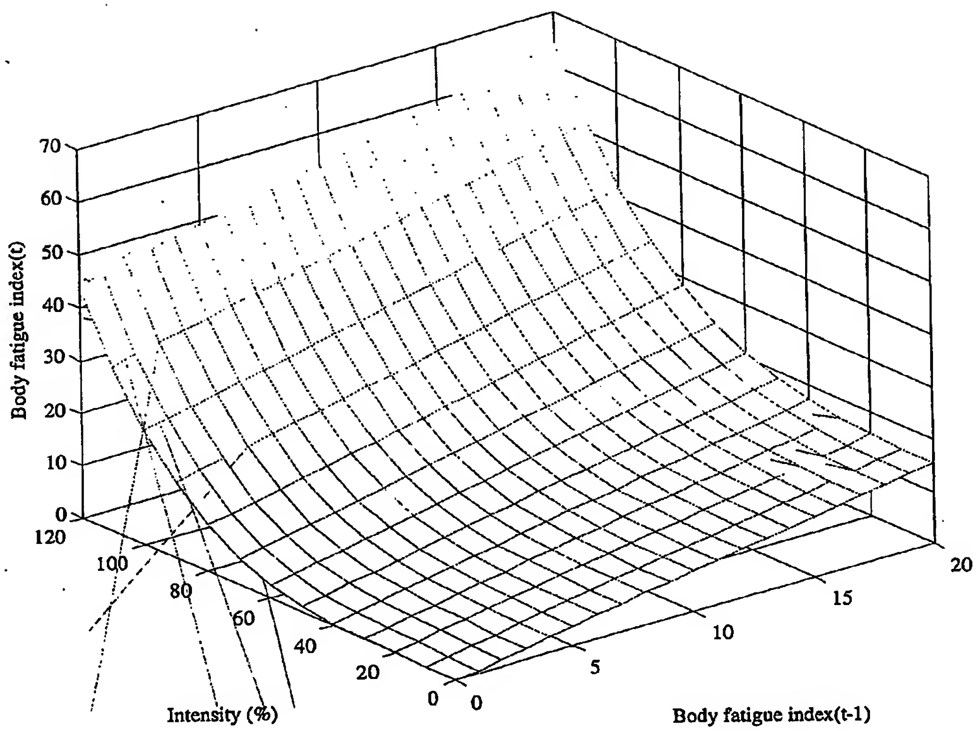

Figure 1

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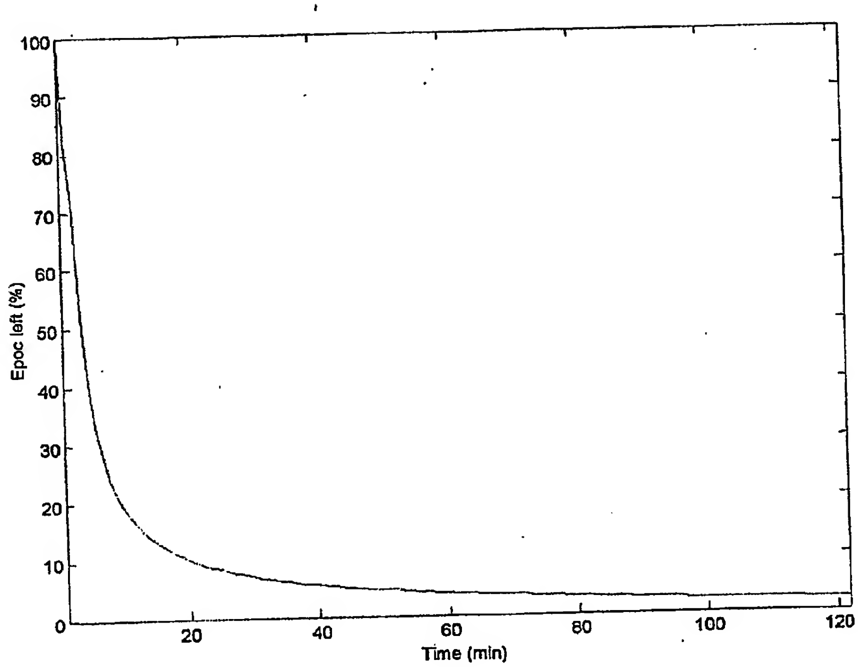
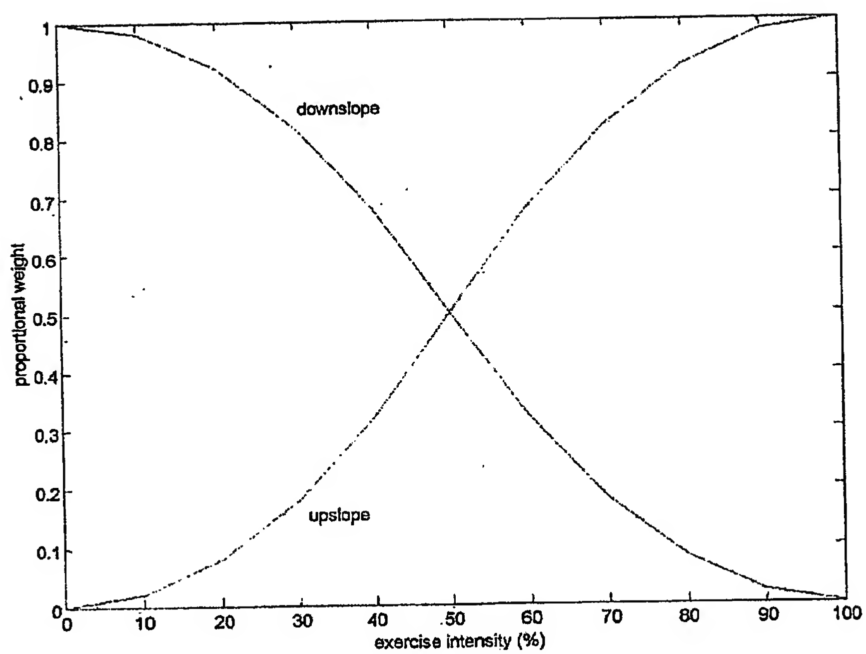
2



100
90
80
70
60
50
40
30
20
10
0
Epoc left (%)
20
40
60
80
100
120
Time (min)

Figure 2

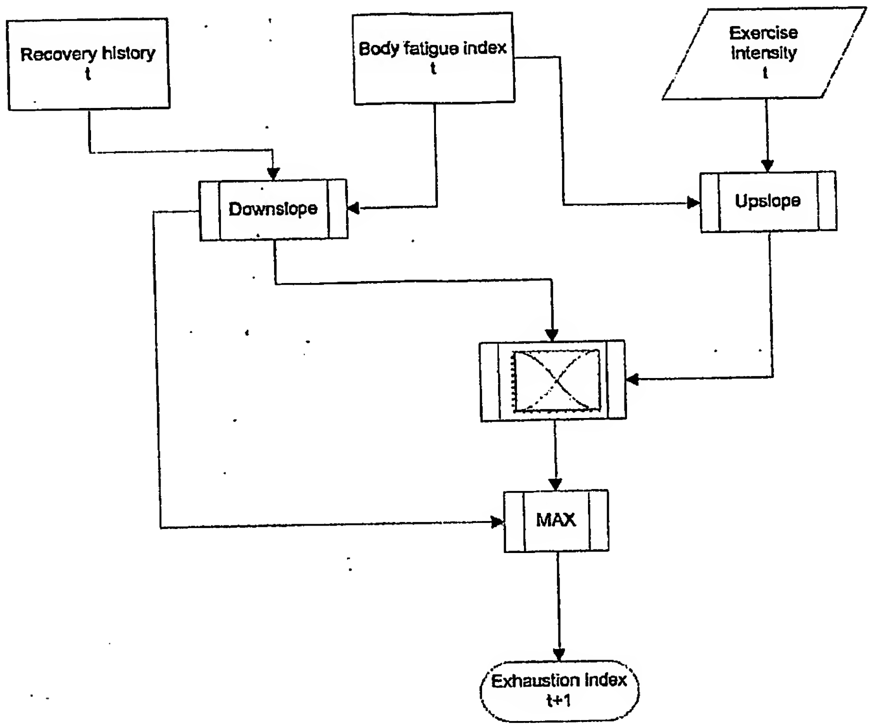
L4 3



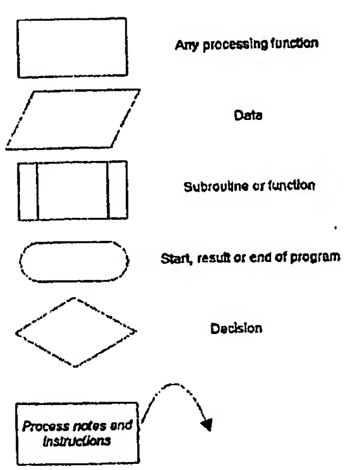
downslope
upslope
proportional weight
exercise intensity (%)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
80
90
100

Fig. 3

L4 4



Symbols



Abbreviations in formulas

X	exercise intensity
EX	exhaustion time
DS	downslope
US	upslope

Figure 4

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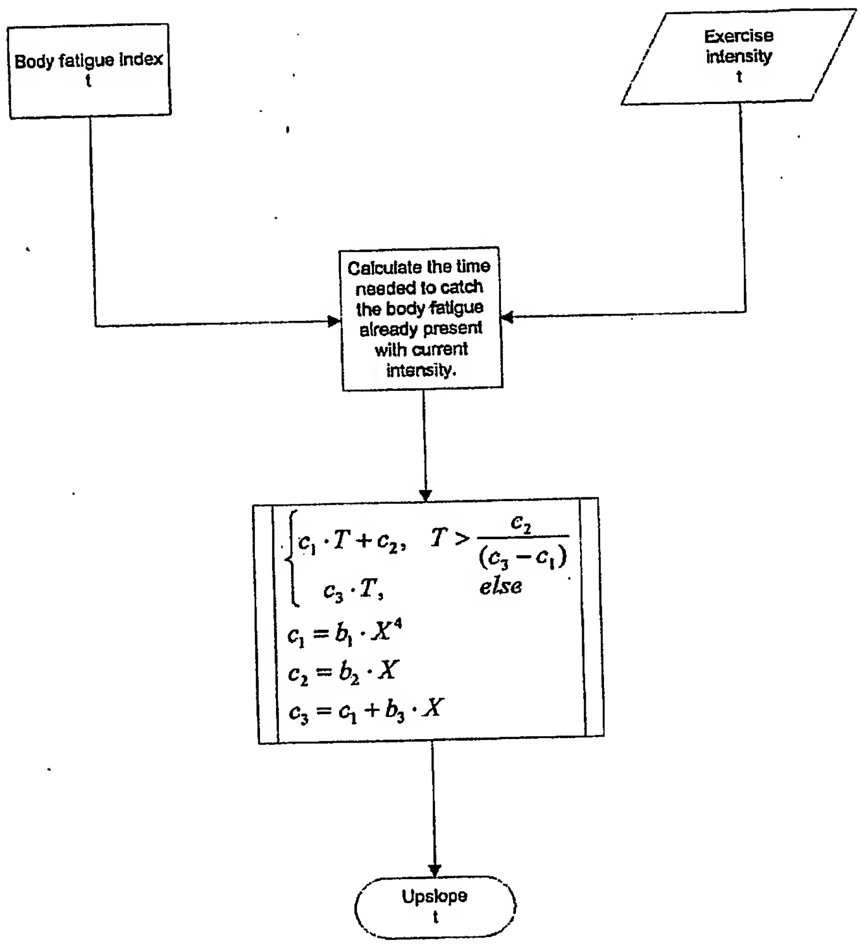
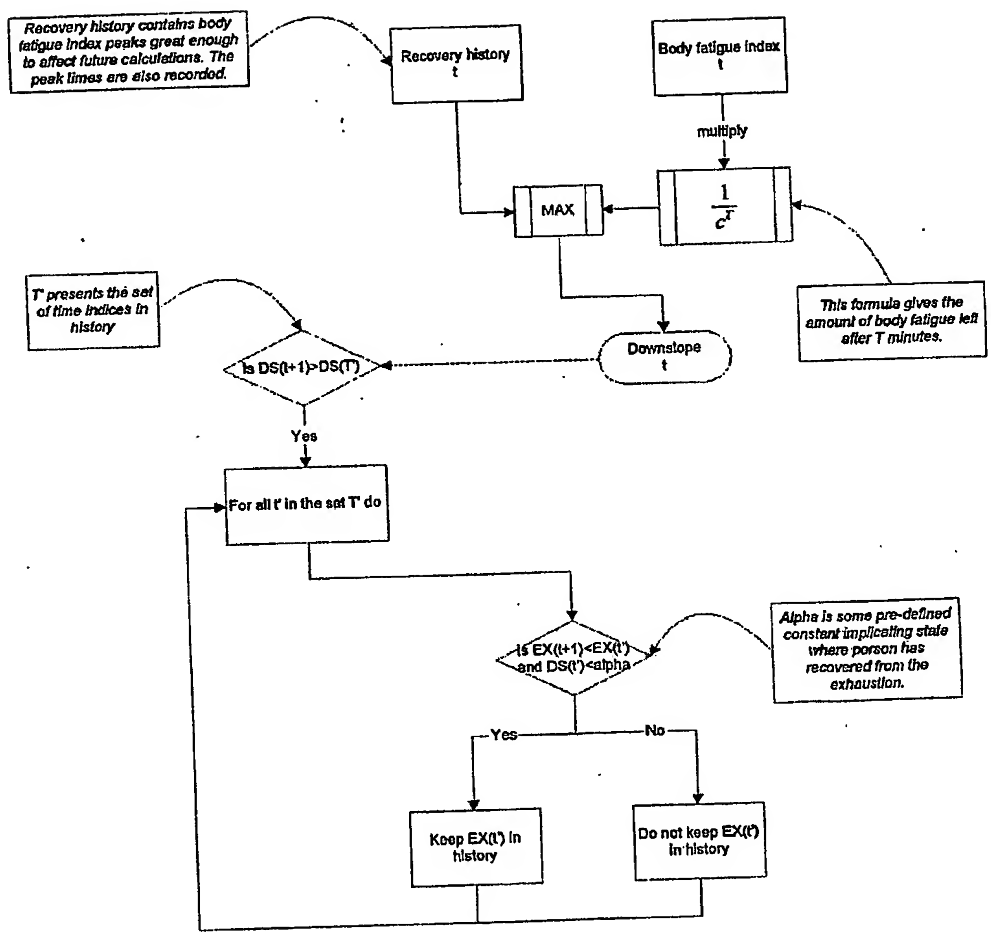

Body fatigue index
t
Exercise intensity
t
Calculate the time needed to catch the body fatigue already present with current intensity.
$\begin{cases} c_1 \cdot T + c_2, & T > \frac{c_2}{(c_3 - c_1)} \\ c_3 \cdot T, & else \end{cases}$
$c_1 = b_1 \cdot X^4$
$c_2 = b_2 \cdot X$
$c_3 = c_1 + b_3 \cdot X$
Upslope
t

Figure 5

L4

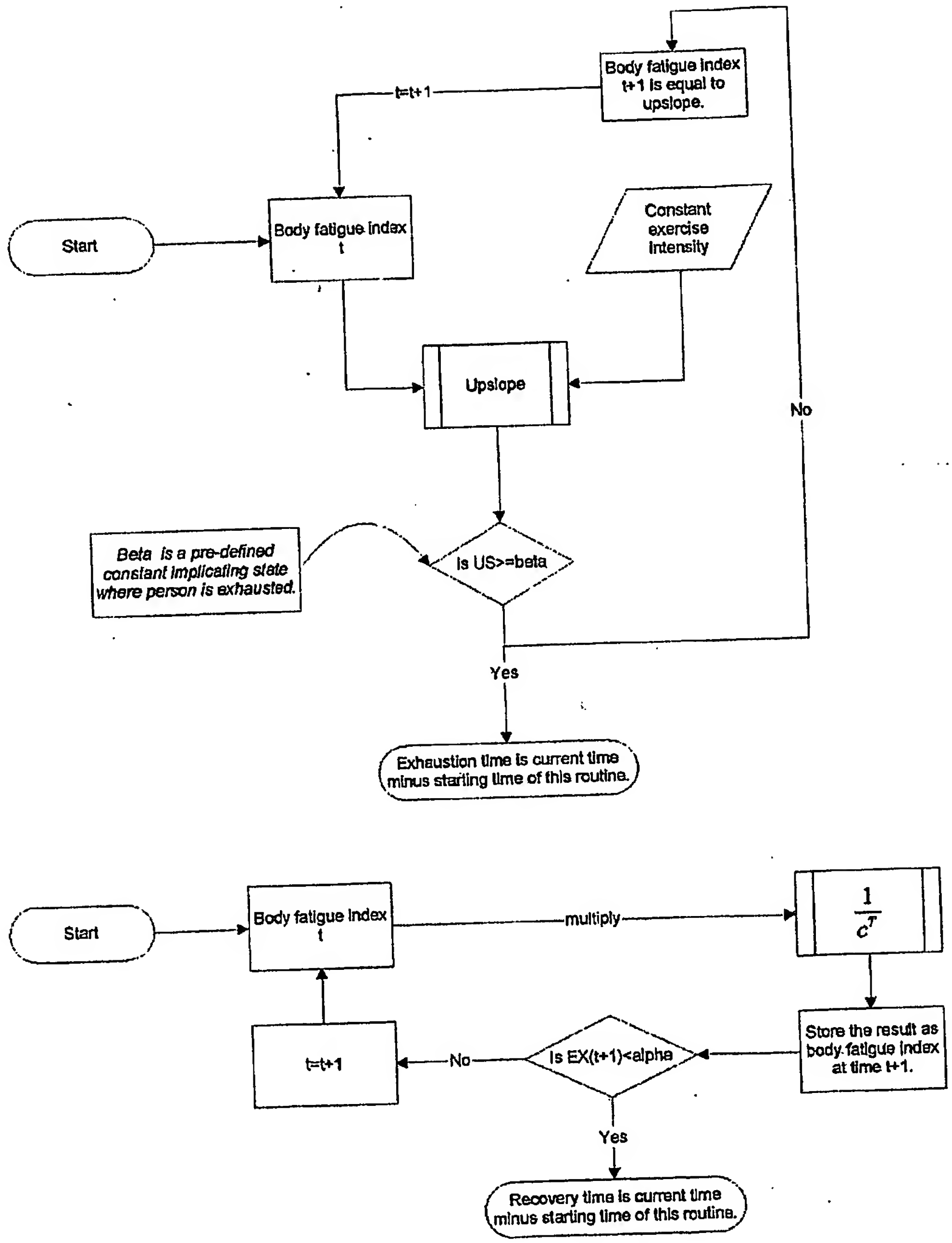
6



Recovery history contains body fatigue index peaks great enough to affect future calculations. The peak times are also recorded.
Recovery history
t
Body fatigue index
t
multiply
MAX
$\frac{1}{c^T}$
This formula gives the amount of body fatigue left after T minutes.
T' presents the set of time indices in history
Is DS(t+1)>DS(T')
Downslope
t
Yes
For all t' in the set T' do
Is EX((t+1)<EX(t') and DS(t')<alpha
Alpha is some pre-defined constant implicating state where person has recovered from the exhaustion.
Yes
No
Keep EX(t') in history
Do not keep EX(t') in history

Figure 6

L4 7



Body fatigue index t+1 is equal to upslope.
t=t+1
Start
Body fatigue index t
Constant exercise intensity
Upslope
No
Beta is a pre-defined constant implicating state where person is exhausted.
Is US>=beta
Yes
Exhaustion time is current time minus starting time of this routine.
Start
Body fatigue index t
multiply
$\frac{1}{c^T}$
Store the result as body fatigue index at time t+1.
Is EX(t+1)<alpha
No
t=t+1
Yes
Recovery time is current time minus starting time of this routine.

Figure 7

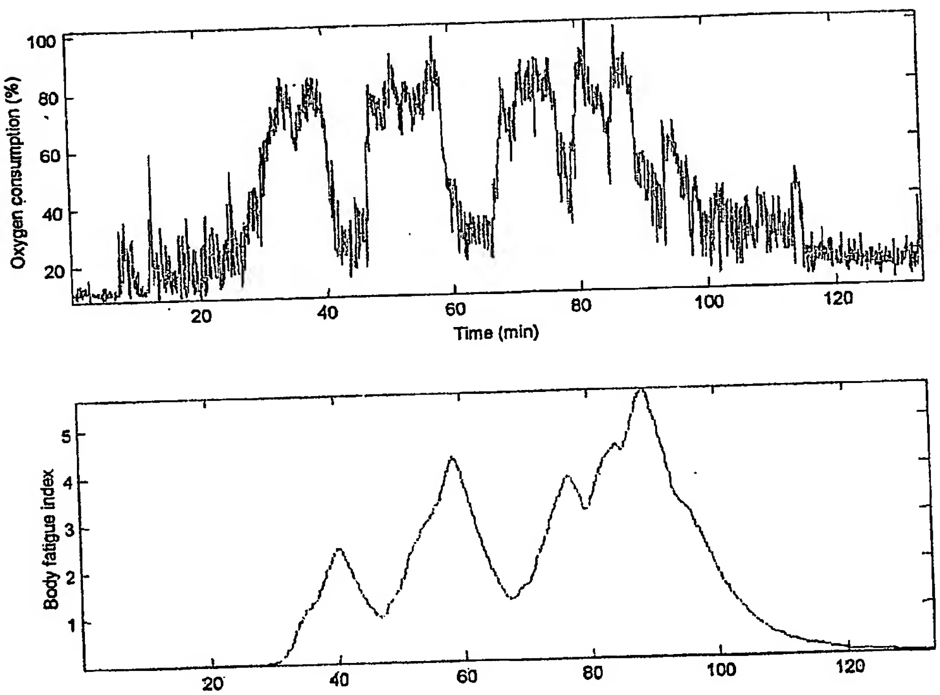

Oxygen consumption (%)
100
80
60
40
20
20
40
60
80
100
120
Time (min)
Body fatigue index
5
4
3
2
1
20
40
60
80
100
120

Fig. 8